Project ID# mat235

# Light Metals Core Program - Thrust 4 - Residual Stress Effects

**Presenter : Ayoub Soulami**

PI : Ayoub Soulami

Team : Kranthi Balusu, Kyoo Sil Choi, Lei Li

**Pacific Northwest National Laboratory**

PNNL is operated by Battelle for the U.S. Department of Energy

LMCP Thrust 4 C2 OVERVIEW

**LMCP Thrust 4 Crosscut**
**MAT235: LMCP - Thrust 4 - Residual Stress Effects, Ayoub Soulami, Pacific Northwest National Laboratory**

# Overview

## Timeline

- Lab Call Award – September 2020
- Kickoff – November 2020
- End – September 2023
- 50% Percent complete

## Budget

| Thrust 4 Crosscutting Thrust | | |
|---|---|---|
| **Project** | **Title** | **FY22** |
| Various | Advanced Characterization, High Performance Computing (PNNL) | $250k |
| Various | Advanced Characterization, High Performance Computing (ORNL) | $300k |
| Various | Advanced Characterization (ANL) | $200k |
| C1 | Thrust 4 - Materials Lifecycle (ANL) | $150k |
| C2 | Residual Stress Effects (PNNL) | $250k |
| | Totals | $1.15m |

## Barriers and Technical Targets

- **An integrated suite of computational models** would enable accelerating the product development cycle time from initial materials development to prediction of parts performance*
- Assist local properties enhancement projects in understanding **residual stresses** and make sure to maintain the dimensional stability of the processed parts
- * USDRIVE Materials Technical Team Roadmap, October 2017

## Partners

- Project Partners (all LMCP projects)
  - Pacific Northwest National Laboratory
  - Oak Ridge National Laboratory
- Partner Laboratories
  - Argonne National Laboratory

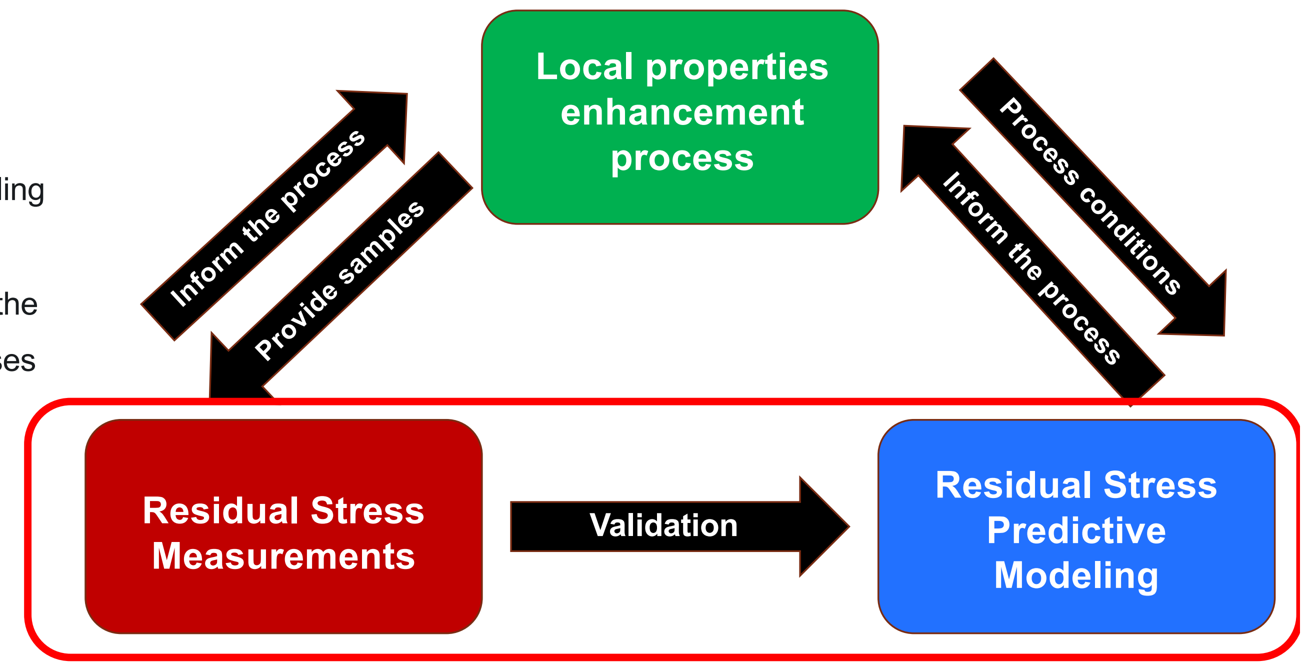
# Relevance

- Selective processing will create gradients in microstructure, performance and will lead to residual stresses and potential dimensional instability
- Develop a combined experimental-computation framework to accurately measure and predict residual stresses resulting from local property enhancement processes.
- Help establish the optimum process parameters to reduce residual stresses and guarantee dimensional stability.
- Assist in developing potential stress relief procedures without altering the strength of the material/part

Distorted FSPed Al 5182 sheet sample

# Approach

- Work with all projects within LMCP
- Collect samples for residual stress measurements and characterization
- Develop and validate predictive modeling tools
- Conduct parametric studies to inform the local properties enhancement processes on how to:
  - Reduce and mitigate residual stresses
  - Control dimensional instabilities



# FY22 Milestones (need to update)

| Milestone | Due Date | Type | Milestone | Status |
|---|---|---|---|---|
| M1.0 | 3/31/2022 | Quarterly Progress Measure (Regular) | Validate the predicted residual stresses resulting from FSP and UW of Al sheets and Al/Mg Castings | Milestone Achieved |
| M2.0 | 9/30/2022 | Quarterly Progress Measure (Regular) | Predict and validate residual stresses resulting from locally enhanced properties on large components | In progress |

Pacific Northwest NATIONAL LABORATORY

# Residual Stresses during FSP

## Development of the Thermo-Pseudo Mechanical (TPM) Model

FSP of Al sheet, Al/Mg Castings

**1C1** **2A1** **3B**

Heat source model – Heat generation from friction and material flow is approximated using an analytical relation[1]

Friction Stir Tool as a heat source (as a subroutine)
$q_{total} = f(\sigma_{yield})$

$q_{total}$

Thermo-Mechanical Analysis using Finite Elements - FEA

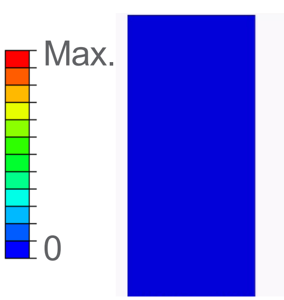
**Pseudo-Coupling**

$\sigma_{yield}$

$\sigma_{yield}$

$T, \varepsilon, \dot{\varepsilon}$

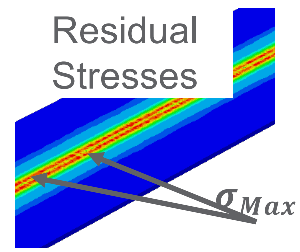
**Surface Heat flux**

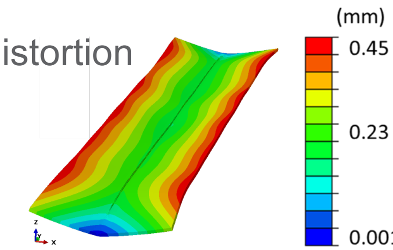


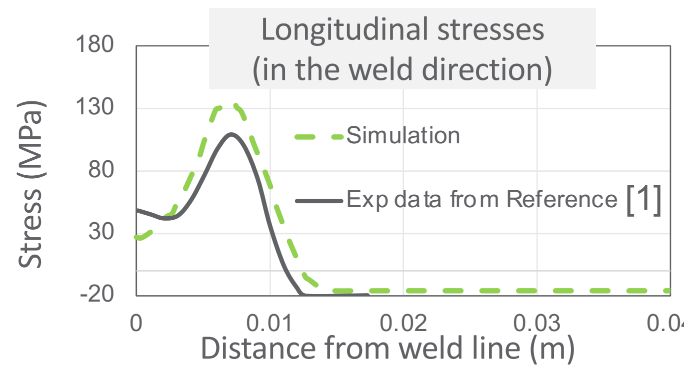

Half model assuming symmetry

Constitutive material behavior models for

1) Plastic flow
2) Heat induced precipitation softening (as a subroutine)




Developed a validated capability to predict residual stresses and associated distortion resulting from friction stir processing

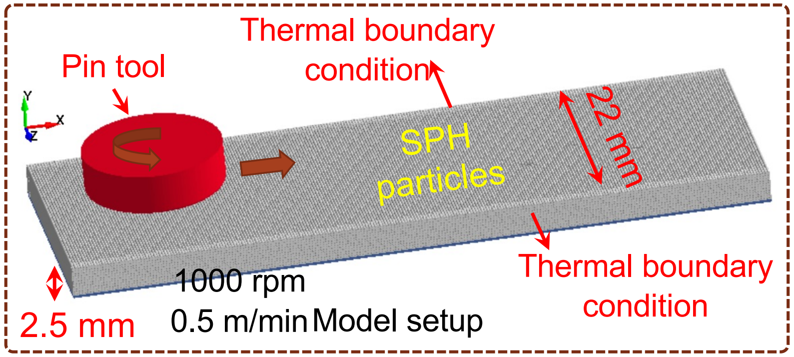
[1] Sonne, M. R., Tutum, C. C., Hattel, J. H., Simar, A., & De Meester, B. (2013). The effect of hardening laws and thermal softening on modeling residual stresses in FSW of aluminum alloy 2024-T3. Journal of Materials Processing Technology, 213(3), 477–486. https://doi.org/10.1016/j.jmatprotec.2012.11.001

Pacific Northwest
NATIONAL LABORATORY

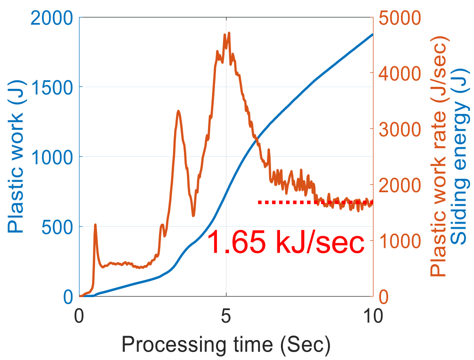
# Residual Stresses during FSP
# Development of SPH Model for FSP of AA7075-T6

FSP of Al sheet

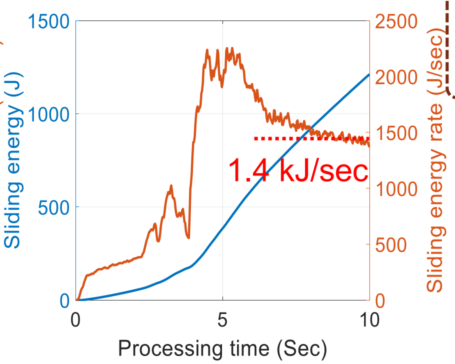
**1C1**



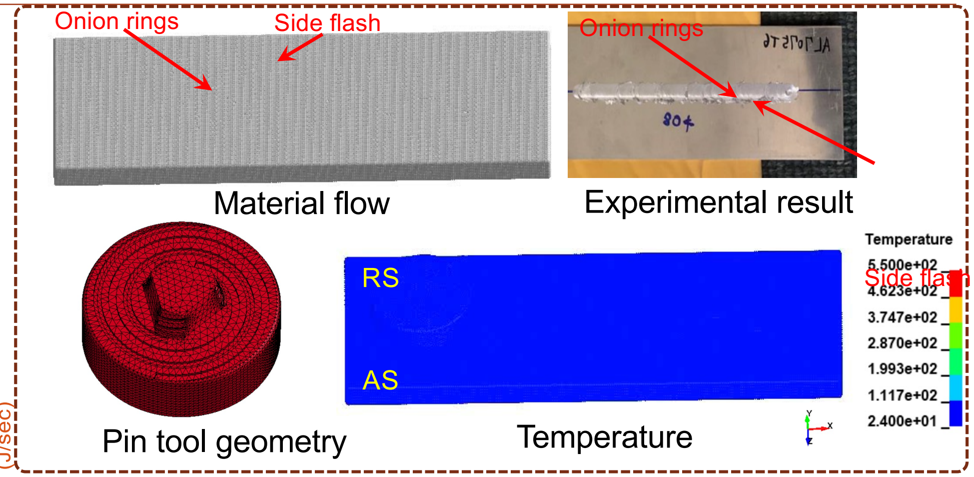
Model setup

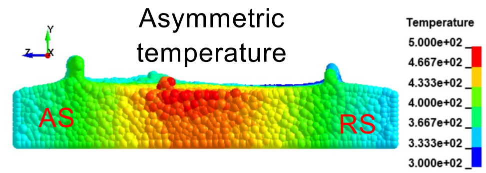


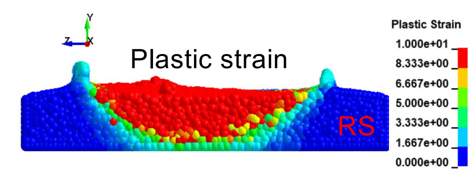
Steady-state plastic work rate

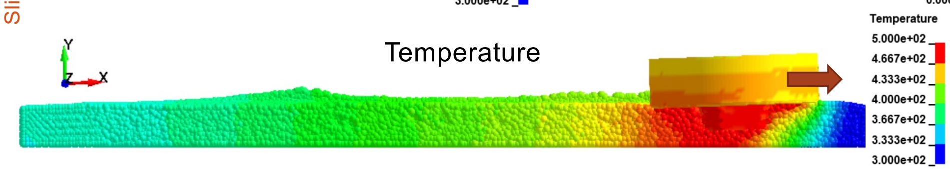


Steady-state sliding energy rate




SPH allows us to obtain high-fidelity predictions of steady-state heat generation rates during FSP

Pacific Northwest
NATIONAL LABORATORY

# Residual Stresses during FSP

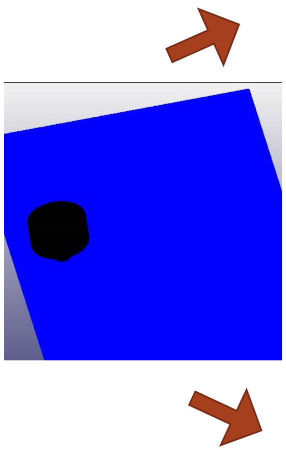
## Coupling Smoothed Particle Hydrodynamics (SPH) with Finite Element Analysis (FEA)

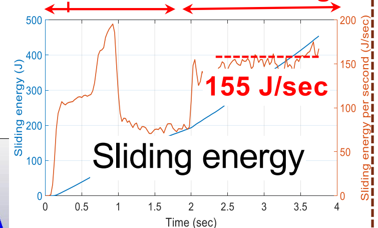
FSP of Al sheet, Al/Mg Castings

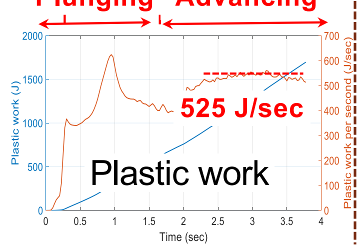
1C1 2A1 3B

Coupled SPH-FEA computationally cheaper (w.r.t SPH) and more accurate (w.r.t TPM in FEA)

**SPH**

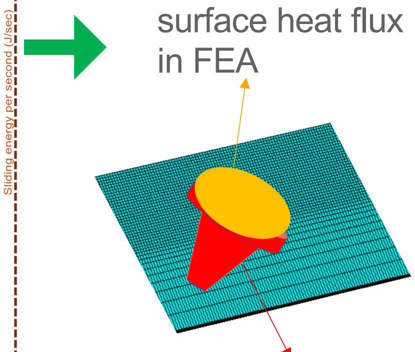




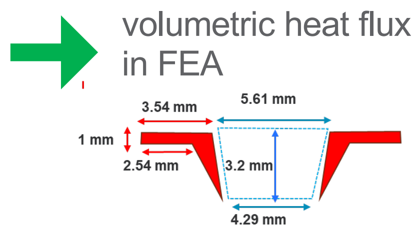




**FEA**

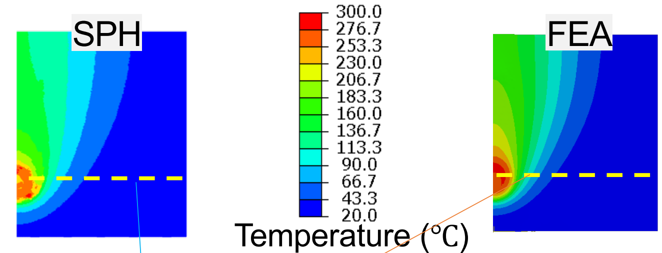
User defined surface heat flux in FEA

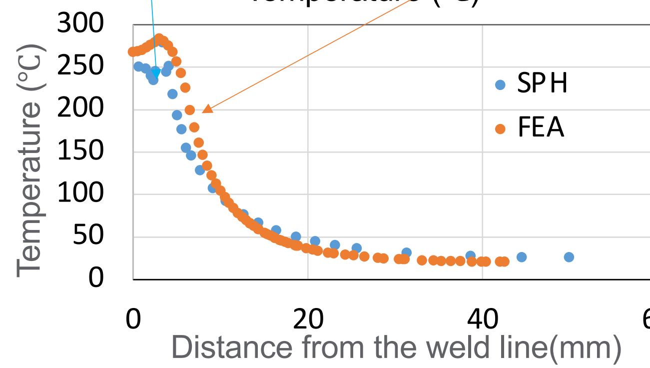


User defined volumetric heat flux in FEA




Comparison of the temperature profiles at the steady-state




- Temperature profiles in SPH and FEA are similar
- SPH-FEA coupling approach works

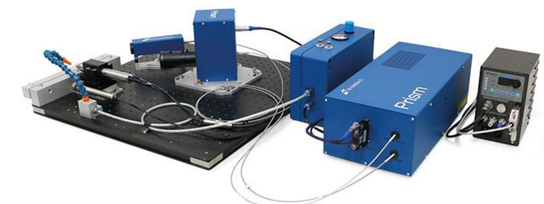
Pacific Northwest NATIONAL LABORATORY

# Residual Stresses during FSP
# Residual Stress Measurement for FSP Samples

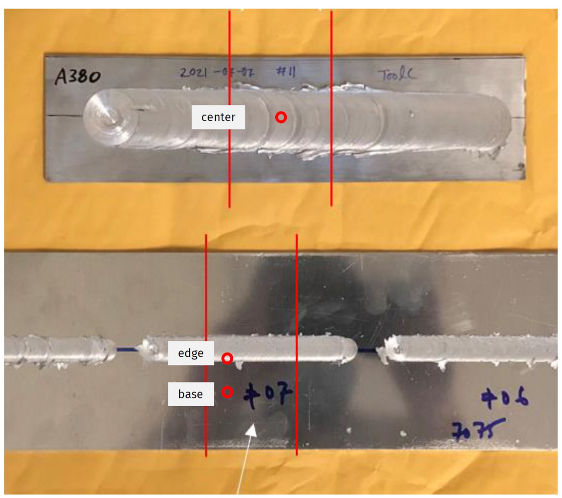
FSP of Al/Mg Castings

2A1 3B

- Residual stress measurement are used for FE modeling validations
- XRD and hole drilling methods were used for measurements
  - A7075-T6 and A380 FSP samples
  - Surface line profiles and depth profiles along transverse directions
  - Two methods show relatively similar results beyond depth of ~50μm
- Hole drilling system is to be used for measurement to support other projects

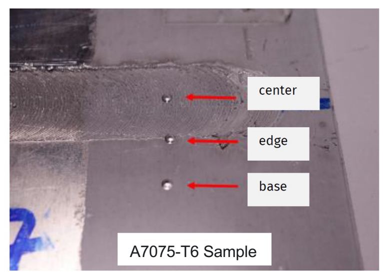


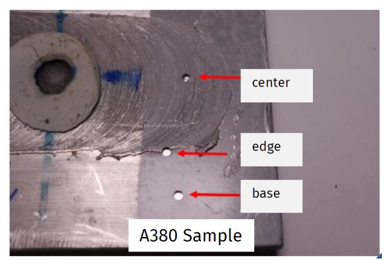

ESPI hole drilling system*



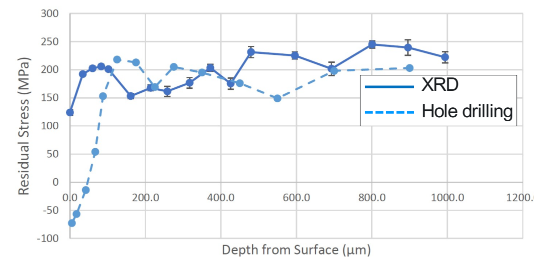

Approximate measurement locations

Line profile locations for two samples

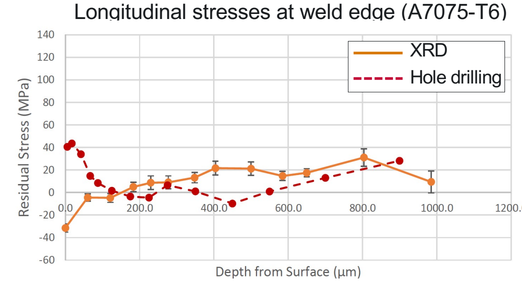



Depth profile locations for two samples




Longitudinal stresses at weld edge (A7075-T6)




Transverse stresses at weld center (A380)

Residual stresses measured from two methods

*https://www.stresstech.com/products/prism/

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Pacific Northwest NATIONAL LABORATORY

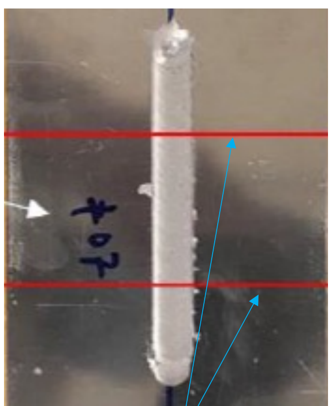
# Residual Stresses during FSP
## Prediction and Validation for Sheet Al Alloy

FSP of Al sheet

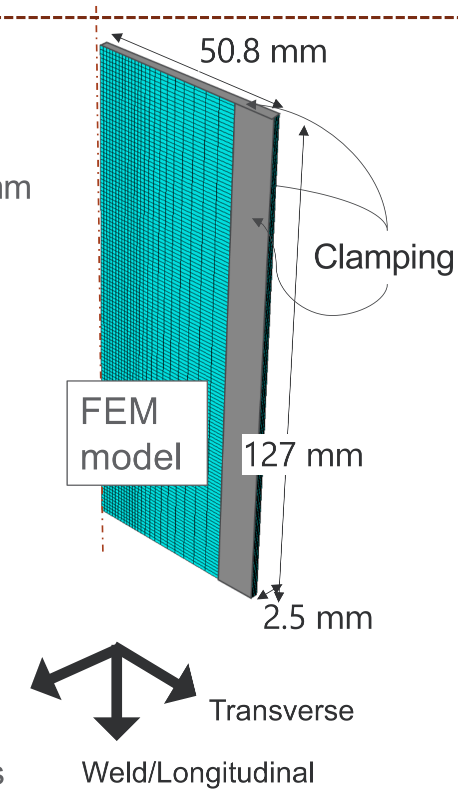
1C1

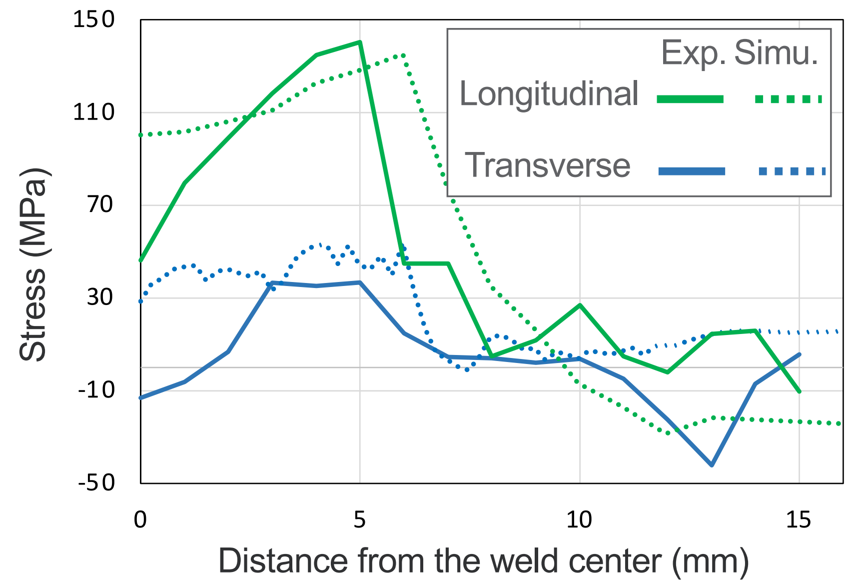
FSP on a Al7075-T6 sample

**Process parameters**
RPM=1000
Weld speed=0.5 m/min
Tool shoulder dia. = 12.7 mm




Probing locations for Xray diffraction (XRD) to characterize residual stresses




- Peak residual stress prediction is accurate
- Discrepancies near the nugget zone

Pacific Northwest NATIONAL LABORATORY

# Residual Stresses during FSP Prediction and Validation for Cast Al Alloy

FSP of Al sheet

**2A1**

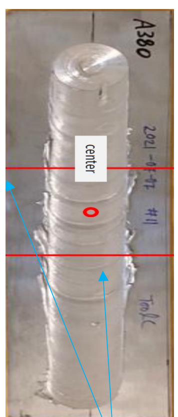
## FSP on a Al380 sample

**Process parameters**

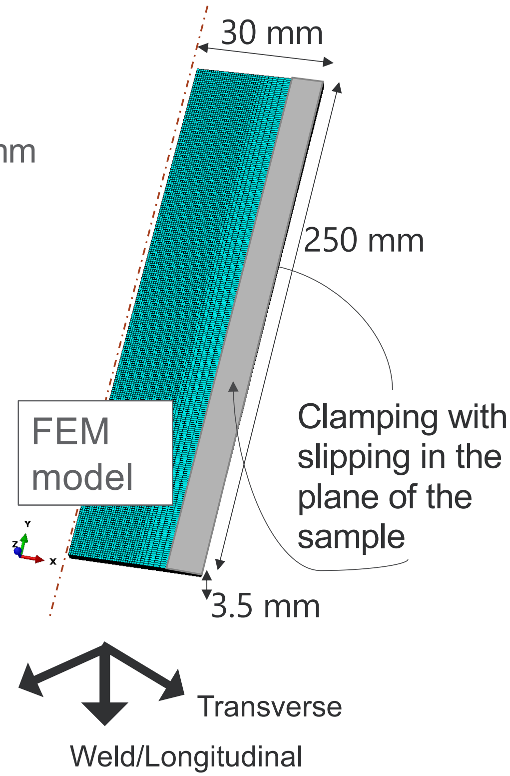
RPM=900

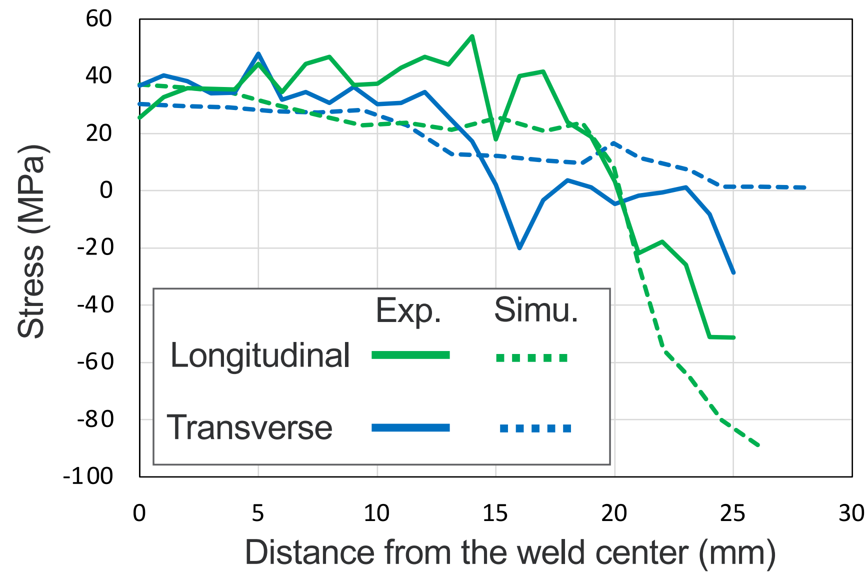
Weld speed=0.1 m/min

Tool shoulder dia. = 30 mm




Probing locations for Xray diffraction (XRD) to characterize residual stresses




- Distributions roughly match
- Discrepancies near
  - The edge of the shoulder
  - Clamped regions

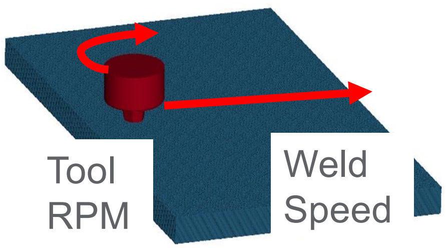
Pacific Northwest NATIONAL LABORATORY

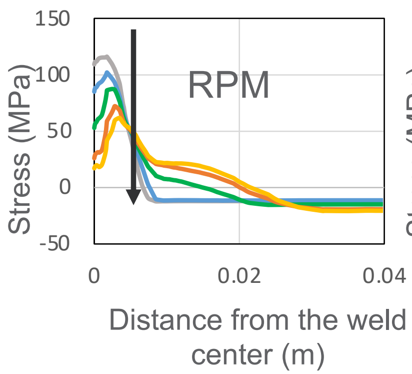
# Residual Stresses during FSP
## Effect of Process Parameters and Clamping Conditions

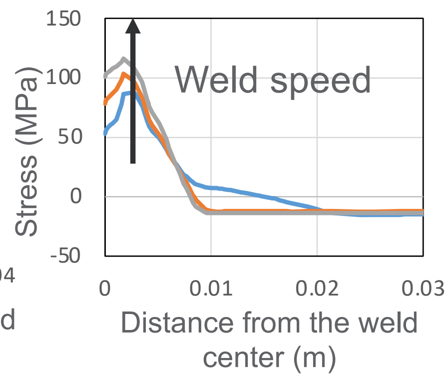
FSP of Al sheet, Al/Mg Castings

1C1 2A1 3B

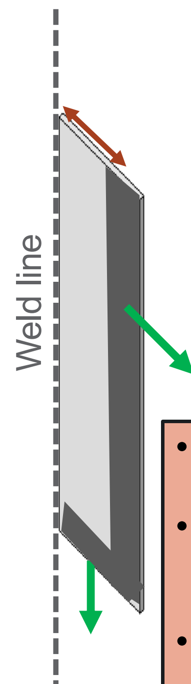
### Process parameters

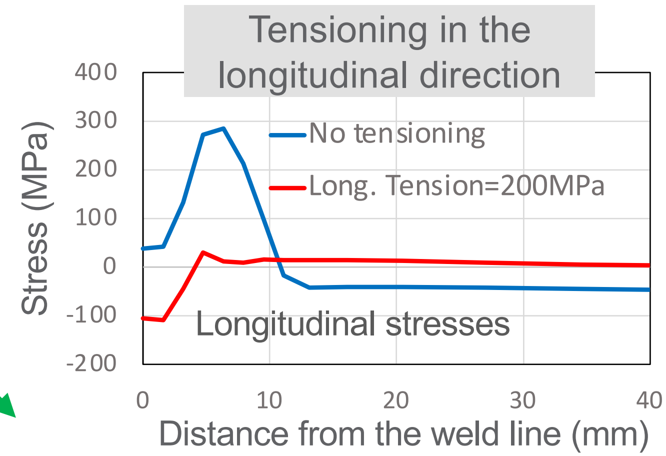



### Clamping conditions



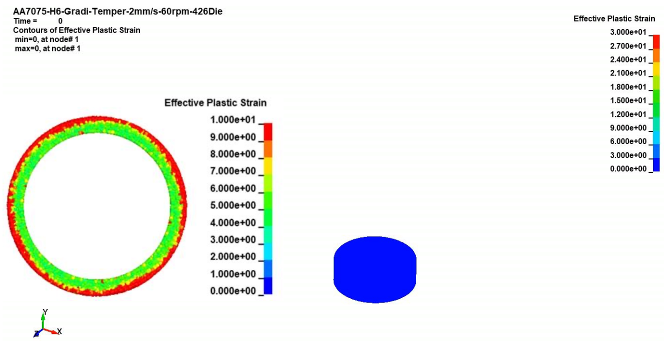




- Effective mitigation through longitudinal tensioning
- Ineffective tensioning approaches
  - Displacement controlled tensioning
  - Tensioning in the transverse direction
- Clamping at distances further from the weld line reduces the residual stresses

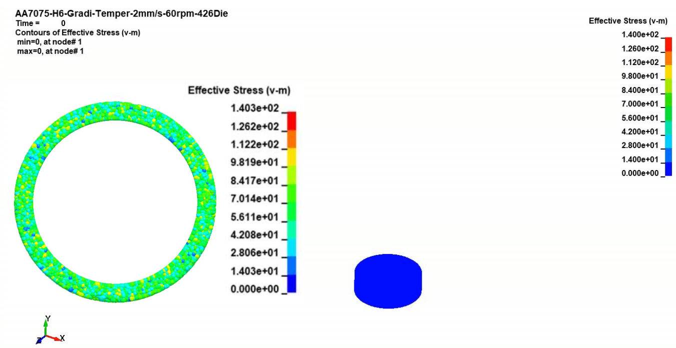
Pacific Northwest
NATIONAL LABORATORY

# Residual Stresses during ShAPE tube extrusion; Modeling tube extrusion/quenching

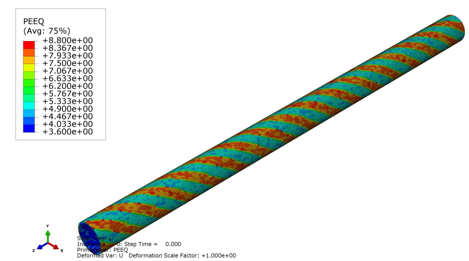





**Plastic strain evolution during extrusion**

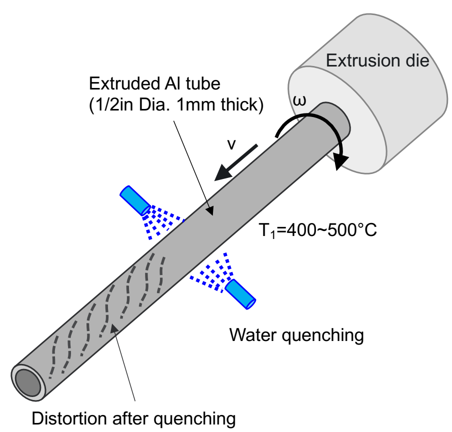



**Mises stress evolution during extrusion**

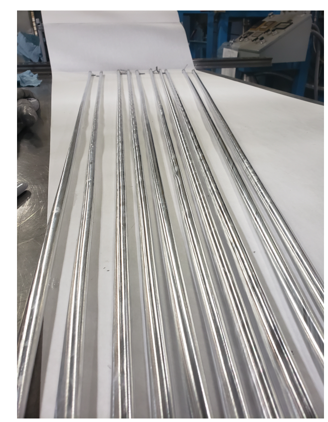



**Example of initial strain distribution in tube**

- Goal: Identify the sources for the waviness/distortion observed after water quenching on ShAPE extruded aluminum tube and suggest solutions
- Obtained stress/strain distribution information from SPH simulations to find how they are distributed from ShAPE processing




**Schematic of quenching-induced distortion**



**Extruded aluminum tubes showing distortion**

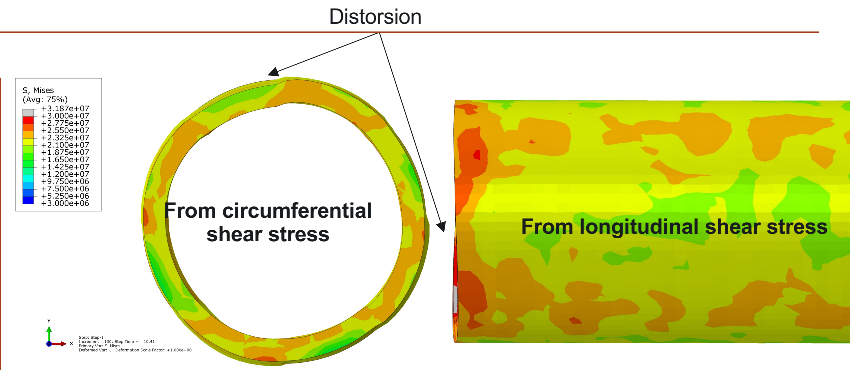
TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Pacific Northwest NATIONAL LABORATORY

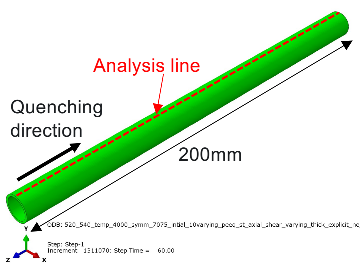
# Residual Stresses during ShAPE tube extrusion
# Residual Stress / distortion predictions



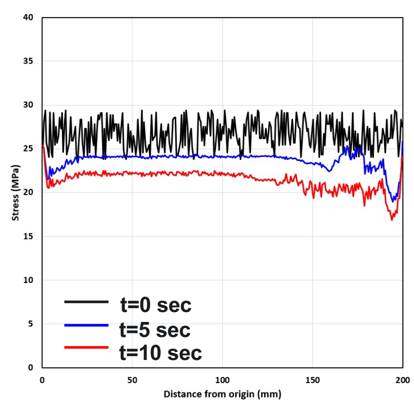
- With all the inhomogeneity/aspects considered in the model, no noticeable quenching-induced distortion was observed
- Small distortion could be observed in the model, these distortions are observed to occur before quenching
- After quenching, stresses (e.g., S11, S33) tend to be slightly lower compared to those in un-quenched region and to be compressive, which might increase the possibility of buckling/distortion



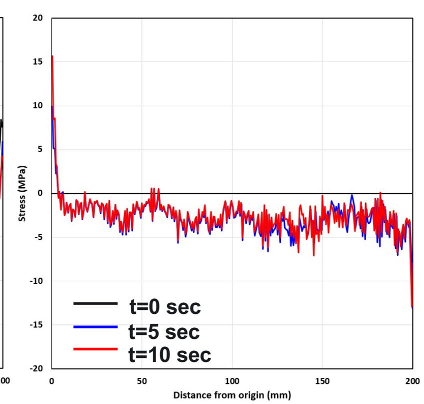

Examples of tube shape (for 27MPa ±10%)



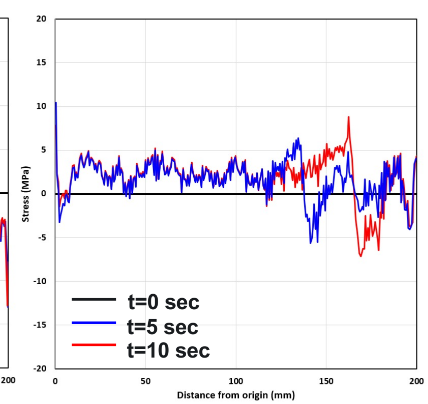

Location for stress plots




Mises stress




Hoop stress (S11)

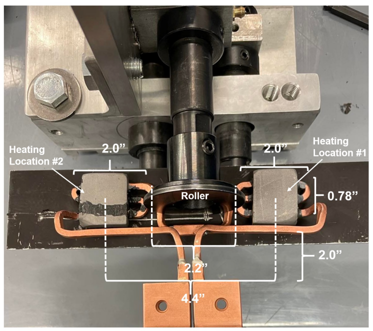



Axial stress (S33)

# Residual Stresses during bending-unbending; Bending-unbending process modeling

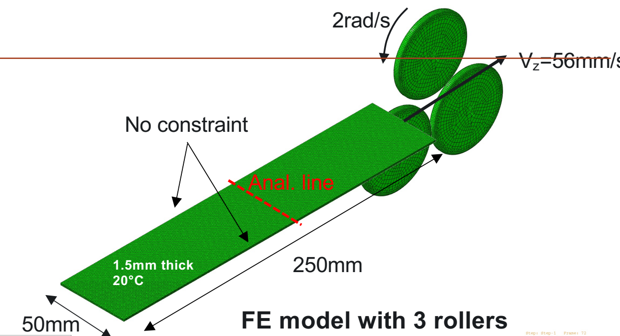
Al Sheet bend-unbend

1C1

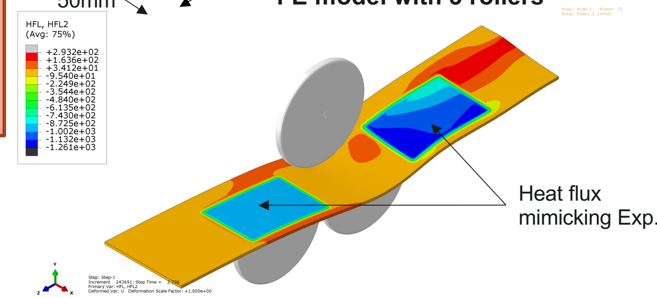


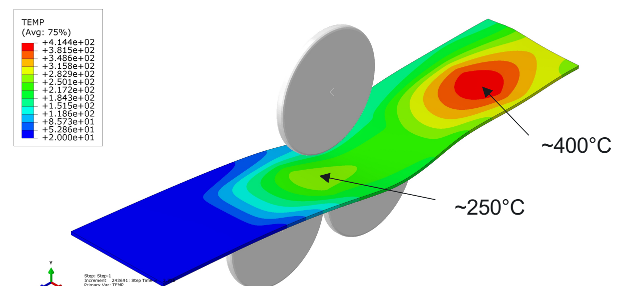

**Experimental setup for heating**
**IR cameras are used for Temperature measurements**

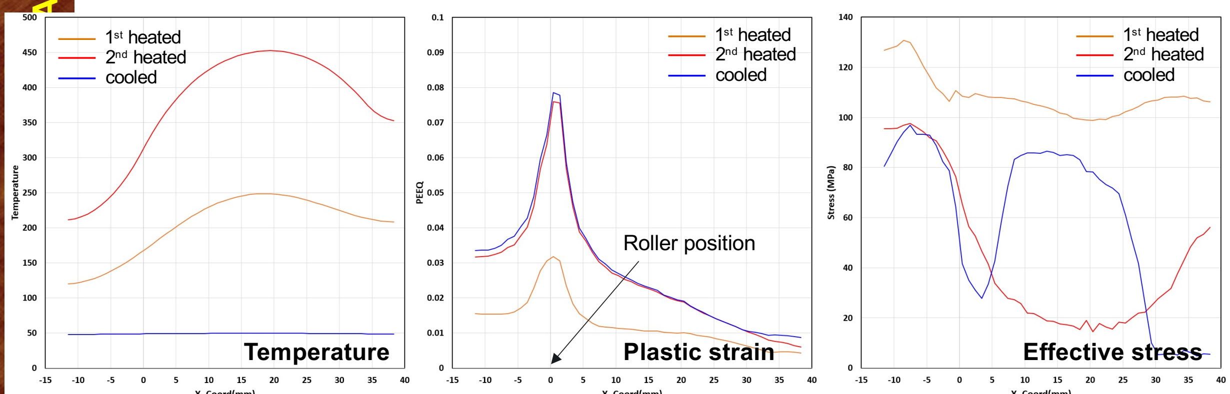
- Finite Element model was developed to help build the experimental setup and predict residual stresses in the future
- Temperature profiles similar to experimental messurement were obtained for 1st and 2nd heating (~250°C and ~400°C)
- Longitudinal/transverse stress components are observed to be compressive along/near bend/unbend line




**FE model with 3 rollers**




**Profiles along analysis line (on top surface)**

# Collaboration and Coordination with Other Institutions

- As a cross cutting project, we are supporting several projects within the LMCP program

| Project | Title |
|---|---|
| 1A | Sheet Materials with Local Property Variation (PNNL/ANL) |
| 1B | Form-and-Print - AM for Localized Property Enhancement of High-strength Al sheet (ORNL) |
| 1C1 | Local Thermomechanical Processing to Address Challenges to Implementing High Strength Al Sheet (PNNL) |
| 1C2 | Local Thermomechanical Processing to Address Challenges to Implementing High Strength Al Sheet (ORNL) |
| 2A1 | Solid Phase Processing of Aluminum Castings (PNNL) |
| 2A2 | Power Ultrasonic Surface Processing of Die Cast Al Alloys (ORNL) |
| 2B | High-intensity Thermomechanical Processes for Enhanced Strength, Fatigue Resistance and Ductility in Al Castings (PNNL) |
| 2C | Cast and Print (ORNL) |
| 3A1 | Cast magnesium alloy surface modifications to improve the corrosion performance- Reactive Processes (ORNL) |
| 3A2 | Cast magnesium alloy surface modifications to improve the corrosion performance- Surface Alloying (PNNL) |
| 3B | Local Thermomechanical Property Modification of Magnesium Castings via Solid-Phase Processing techniques (PNNL) |

# Responses to Previous Years Review Comments

- This project was not reviewed previously

# Remaining Challenges and Barriers

- Prioritization plan for residual stress measurements using PNNL and ORNL resources
- Transition from coupons to predicting residual stresses in processed parts/components
- Assist different projects within LMCP in optimizing their processing conditions when dealing with complex geometries

# Proposed Future Research

- Establishment of methods to characterize, predict and optimize micro and macro residual stress in Al and Mg alloys after local processing methods developed in LMCP **(PNNL)**
- Work with ORNL PIs on predictive modeling and residual stress measurements **(ORNL)**
- Focus on predicting and measuring residual stresses in large parts/components **(PNNL/ORNL)**

Any proposed future work is subjected to change based on future funding levels

# Summary

- **Technical summary**
  - Developed **SPH and TPM** model for residual stress prediction in **FSP**
  - Measured residual stresses in **FSPed Al sheet and casting**
  - Simulation of the effect of **stress mitigation techniques** (Process parameters, Clamping conditions, Tensioning)
  - FE model was developed to identify the sources for the quenching-induced distortion of **ShAPE-extruded aluminum tube**
  - Simulations for various conditions/inhomogeneity were performed to examine their effects on the tube distortion
  - Model was developed to examine the effect of heating temperature on the residual stresses during **bend/unbend process**
- **Impact on DOE mission**
  - Developed a combined experimental-computation framework to accurately measure and predict residual stresses resulting from local property enhancement processes.
  - **ICME** tools are being developed, validated, and used to help ensure dimensional stability of parts/components